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Mapping land use changes resulting from biofuel production and the effect of mitigation measures

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Abstract

Many of the sustainability concerns of bioenergy are related to direct or indirect land use change (LUC) resulting from bioenergy feedstock production. The environmental and socio-economic impacts of LUC highly depend on the site-specific biophysical and socio-economic conditions. The objective of this study is to spatiotemporally assess the potential LUC dynamics resulting from an increased biofuel demand, the related greenhouse gas (GHG) emissions, and the potential effect of LUC mitigation measures. This assessment is demonstrated for LUC dynamics in Brazil towards 2030, considering an increase in the global demand for bioethanol as well as other agricultural commodities. The potential effects of three LUC mitigation measures (increased agricultural productivity, shift to second-generation ethanol, and strict conservation policies) are evaluated by using a scenario approach. The novel modelling framework developed consists of the global Computable General Equilibrium model MAGNET, the spatiotemporal land use allocation model PLUC, and a GIS-based carbon module. The modelling simulations illustrate where LUC as a result of an increased global ethanol demand ($+26 \times 10^9$ L ethanol production in Brazil) is likely to occur. When no measures are taken, sugar cane production is projected to expand mostly at the expense of agricultural land which subsequently leads to the loss of natural vegetation (natural forest and grass and shrubland) in the Cerrado and Amazon. The related losses of above and below ground biomass and soil organic carbon result in the average emission of 26 g CO₂.eq/MJ bioethanol. All LUC mitigation measures show potential to reduce the loss of natural vegetation (18%–96%) as well as the LUC-related GHG emissions (7%–60%). Although there are several uncertainties regarding the exact location and magnitude of LUC and related GHG emissions, this study shows that the implementation of LUC mitigation measures could have a substantial contribution to the reduction of LUC-related emissions of bioethanol. However, an integrated approach targeting all land uses is required to obtain substantial and sustained LUC-related GHG emission reductions in general.

KEYWORDS

agricultural expansion, Brazil, ethanol, GIS, greenhouse gas emissions, indirect land use change, land use change mitigation measures, land use change modelling, sugar cane, sustainability

1 | INTRODUCTION

The use of biomass for energy and materials is considered an essential option for replacing fossil fuels, to mitigate greenhouse gas (GHG) emissions and to contribute to rural and overall economic development (Chum et al., 2011; Dornburg et al., 2010; IPCC 2014; WWI 2006). However, increased dedicated biomass feedstock production could have significant adverse environmental and socio-economic effects such as deforestation, impact on soil, water and biodiversity as well as a decrease in food security and local well-being (Chum et al., 2011; Creutzig et al., 2015; Smith et al., 2014; Wicke, Vuuren, Verweij, Van Meijl, & Faaij, 2012). Many of the sustainability concerns of the use of biomass for energy and materials are related to direct or indirect land use change (LUC) resulting from biomass feedstock production (Wicke et al., 2012). Therefore, expansion of biomass production for energy and materials requires monitoring and good governance of land use. In order to develop effective policy strategies, it is important to understand LUC dynamics resulting from biomass feedstock production and how negative effects of LUC s can be avoided or minimized.

In recent years, several studies have tried to quantify (in-) direct LUCs resulting from biofuel production. Most of these studies made use of Computable General Equilibrium (CGE) or partial equilibrium (PE) models in order to capture market mechanisms and competition (Al-Riffai, Dimaranan, & Laborde, 2010a; Laborde, 2011; Searchinger et al., 2008; Taheripour & Tyner, 2013; Tyner, Taheripour, Zhuang, Birur, & Baldos, 2010). However, comparison of the results of these modelling efforts shows large differences in terms of magnitude of LUC and related GHG emissions (Ahlgren & Di Lucia, 2014; Chum et al., 2011; Edwards, Mulligan, & Marelli, 2010; Warner, Zhang, Inman, & Heath, 2014; Wicke et al., 2012). These variations can be explained by differences in the structures of the models (e.g., level of aggregation of sectors and geographical regions, elasticities, competition and substitution) and in the input data (assumptions on, for example, scenarios, policies, agricultural productivity, technology improvement, location of production, consumption and trade, carbon stocks) (Ahlgren & Di Lucia, 2014; Bauen, Chudziak, Vad, & Watson, 2010; Edwards et al., 2010; Khanna, Crago, & Black, 2011; Warner et al., 2014; Wicke et al., 2012). Furthermore, these studies are not able to capture the dynamic nature of (indirect) LUC (Wicke et al., 2012).

As LUCs are driven by interactions among cultural, technological, biophysical, political, economic, and demographic forces within a spatial and temporal context (FAO 2010; Geist & Lambin, 2002; Long, Li, Wang, & Jia, 2013), the ability to predict patterns of LUC from a single driver such as changes in commodity prices may be limited (FAO 2010; Plevin, O'Hare, Jones, Torn, & Gibbs, 2010). Moreover, the impacts of LUC (in terms of, for example, GHG emissions, impacts on soil, water, biodiversity, and rural development) highly depend on the site-specific biophysical and socio-economic conditions which vary over space and time. Therefore, the (impact of) biofuel-induced (indirect) LUC should be assessed spatially and temporal explicitly.

The objective of this study is to spatiotemporally assess the dynamics in LUC as a result of an increased biofuel demand, the impact on GHG emissions, and the effect of LUC mitigation measures. This is demonstrated for potential LUC dynamics in Brazil towards 2030, given an increase in the global bioethanol demand and taking into account the developments in the global demand for other commodities. The LUC mitigation measures assessed in this study are improving agricultural productivity, shifting towards second-generation bioethanol, and enforcing strict land conservation policies.

Previous studies on LUC impacts of biofuel production in Brazil have assessed the potential magnitude and location of LUC (Lapola et al., 2010) and the uncertainties thereof (Verstegen, van der Hilst, et al., 2016). In this study, the focus is on assessing the spatiotemporal effects of LUC mitigation measures on LUC dynamics and related GHG emissions. This study makes use of the modelling framework which was developed by Verstegen, van der Hilst, et al. (2016) to assess spatiotemporal dynamics of (indirect) LUCs in Brazil resulting from an increased global ethanol demand.

Brazil is selected as a case study because it is currently the second largest ethanol producer in the world and its production is expected to increase substantially. The annual ethanol production in Brazil increased from 11.5×10^9 L in 1990/91 to 30.2×10^9 L in 2015/16 (UNICA 2017). Projections of future ethanol production in Brazil vary between 46×10^9 and 65×10^9 L in 2020 to meet both growing domestic demands and international blending targets (EPE 2007, 2012; FAPRI-ISU 2012; FIESP and ICONE 2012; Meira Filho & Macedo, 2009; OECD and FAO 2012, 2013, 2014, UNICA 2010). In addition, Brazil

is one of the major producers and exporters of agricultural and agro-food products in the world (FAO, 2013a,b; OECD and FAO 2015), and due to the abundance of natural resources and favourable climate conditions, it has the potential to expand its agricultural production considerably. However, the success of the agricultural sector in terms of growth and the contribution to the GDP (OECD and FAO 2015) has been associated with the loss of ecosystems in the Amazon, Cerrado, and Atlantic forest (Fearnside, 2005; Martinelli, Naylor, Vitousek, & Moutinho, 2010) and LUC-related GHG emissions (Novaes et al., 2017). In this study, it will be assessed to what extent an increase in the global ethanol demand towards 2030 will result in additional LUCs in Brazil, where LUCs are likely to occur, how much GHG emissions will result from that, and how much various strategies could contribute to the mitigation of LUC and LUC-related GHG emissions.

2 | MATERIALS AND METHODS

2.1 | Modelling framework

As Brazil is an important player on international markets of agricultural commodities (OECD and FAO 2015), agricultural developments in Brazil should be assessed in the context of global developments. For that reason, the MAGNET model (a global CGE model; Woltjer & Kuiper, 2014) is employed to model macro-economic developments including the demand and supply of different commodities (e.g., food, feed, fibre, and fuel) towards 2030. It provides information on the relative change in the amount of land that is required for the production of each commodity in each of the 15 world regions included in MAGNET. Brazil, which was originally included as one of the 15 world regions in the MAGNET model, is disaggregated into 6 “macro-regions”: North, MAPITOBA, North East, Centre West, South East, and South (see Appendix S1). The relative change in the land requirements for crop and livestock production for each of these macro-regions in the time frame 2012–2030 derived from MAGNET is the input for the LUC model PCRaster Land Use Change (PLUC; Versteegen, Karssenbergh, van der Hilst, & Faaij, 2012). The land use allocation model is used to include multiple drivers of LUC and to grasp the complex and dynamic nature of LUC. The PLUC model allocates the annual land requirements for each land use type (e.g., sugar cane, cropland, pasture) in every macro-region in Brazil spatially explicitly at a cell size of 25 km². A GIS-based carbon model is applied to calculate the LUC-related GHG emissions given the changes in soil organic carbon (SOC) and above and below ground biomass, taking into account the spatial heterogeneity in land use, soil and climate conditions.

The combined model approach (see Figure 1) should result in a better understanding of the magnitude and the spatial dynamics of (indirect) LUC resulting from an increase in global ethanol demand and the related GHG emissions. By running different scenarios, the effect of potential measures to mitigate LUC on LUC dynamics and related GHG emissions is assessed. The individual components of the modelling framework are explained in the following sections.

2.1.1 | MAGNET model

The modular applied general equilibrium tool (MAGNET) is a recursive dynamic, multiregional, multi-commodity CGE model, covering the entire global economy (Kavallari, Smeets, & Tabeau, 2014). It is based on the standard GTAP model (Banse et al., 2011) and uses the GTAP database version 8 (Narayanan, Aguiar, & McDougall, 2012). This particular CGE model was selected for this study because of its advanced approach of LUC modelling. A full description of the MAGNET model can be found in Woltjer and Kuiper (2014). In this study, MAGNET is used to assess how an increasing demand for ethanol towards 2030 affects LUC dynamics, in relation to the developments in demand for other agricultural products. An increased demand for agricultural products (including bioethanol) can result in the conversion of natural areas into agricultural land (expansion at the extensive margin) or in higher agricultural productivity (expansion at the intensive margin), depending on the elasticity of substitution of agricultural inputs (labour, machinery, fertilizer) and land (Hertel, 2011). A regional land transition approach has been developed based on the work of de Souza Ferreira Filho and Horridge (2014) and advanced by Woltjer (2013). The area of land that is changed from one particular land use type n to another one m depends on the demand for n and m and the land transition elasticity $e_{n,m}$ which is region specific. The land transition elasticities for all land use types in the macro-regions are based on expert knowledge and validated for the LUC transactions in each macro-region for the LUC between 2007 and 2012 (Versteegen, van der Hilst, et al., 2016). In order to apply the MAGNET model for this case study, several adaptations have been made (e.g., aggregation of sectors, disaggregation of regions, adaptations of land transition elasticities, and updates of data), see Versteegen, van der Hilst, et al. (2016) and Appendix S4.

In the MAGNET model, the following land use types are distinguished: sugar crops, wheat, corn, other cereals, paddy rice, oil seed crops, fibre crops, fruit and vegetables, other crops, planted pasture, rangelands, natural forest, planted forest, grass and shrubland, urban, abandoned land, and other (e.g., bare soil). Abandoned land is land

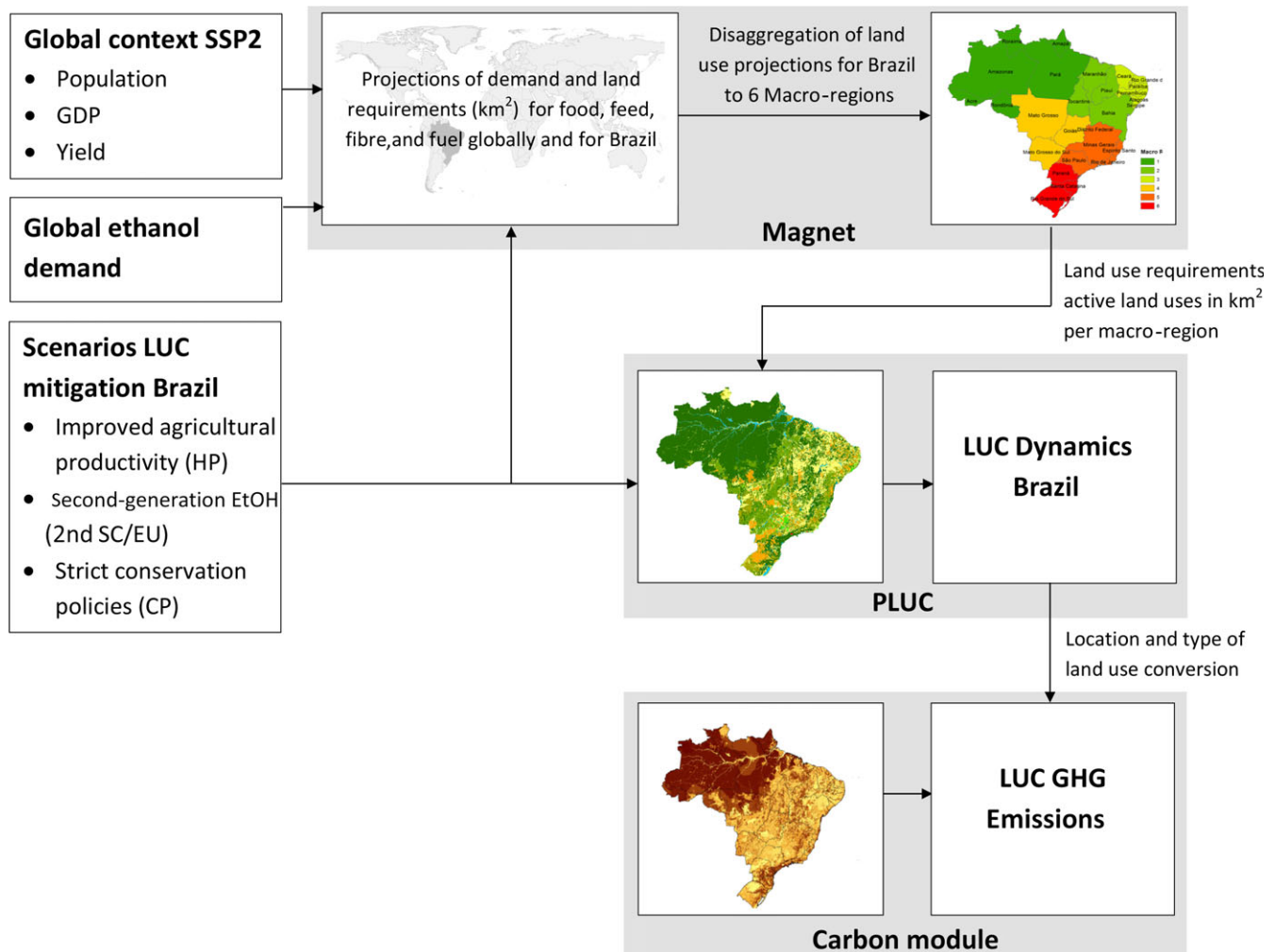


FIGURE 1 Overview of the model framework combining the global Computable General Equilibrium (CGE) model MAGNET, the land use change model PLUC, and the GIS-based carbon module to assess land use change dynamics and related GHG emissions resulting from bioethanol production in Brazil, and the effects of LUC mitigation measures

previously but no longer in use as agricultural land (cropland, pasture, rangeland) and not (yet) occupied by another land use class. The MAGNET model is run for the period 2012–2030. Based on expected global developments (e.g., population growth, GDP, agricultural productivity, and global ethanol demand), and local projections on technological change, agricultural productivity and land use policies in Brazil, MAGNET projects the development in ethanol production in Brazil, and the land requirements for each land use type for the 6 macro-regions for 5-year interval from 2015 to 2030.

2.1.2 | PLUC model

The PLUC model is developed to assess LUC dynamics and the development in land availability for bioenergy crops spatially and temporally specifically (van der Hilst, Verstegen, Karssenbergh, & Faaij, 2012; Verstegen et al.,

2012). Given developments in demand for different land use types, and the spatial variation in suitability of land for each land use type, it projects over time where LUCs are most likely to occur. By running the model in Monte Carlo, (un-)certainties in model projections can be explored (Verstegen et al., 2012; Verstegen, van der Hilst, et al., 2016). The model has been applied in several regional and national case studies (Diogo et al., 2014; van der Hilst, Verstegen, Zheliezna, Drozdova, & Faaij, 2014; van der Hilst et al., 2012; Verstegen, Karssenbergh, van der Hilst, & Faaij, 2014; Verstegen et al., 2012; Verstegen, van der Hilst, et al., 2016). The adaptations and calibration of the PLUC model for the application to this case study in Brazil are described in Verstegen, van der Hilst, et al. (2016) and in Appendix S5.

The point of departure for the LUC projections is the current (2012) land use system state. In the PLUC model, 11 land use types are distinguished: sugar cane, (other)

cropland, rangeland, planted pasture, natural forest, grass and shrubs, planted forest, urban, water, bare soil, and abandoned land. Five of these are “active,” meaning that their production (and thus area) is assumed to actively respond to market dynamics by expanding or contracting: rangeland, planted forest, crops, sugar cane, and planted pasture. All other land use types are assumed to be static (water and urban) or passive, that is, it is assumed they only change as a result of the dynamics of the active land use types (grass and shrubs, natural forest, bare soil, and abandoned land), see Appendix S5. For each year, the PLUC model spatially allocates the land requirements for each active land use type based on the spatial variability of the suitability for the specific land use, and considering the areas excluded for land use conversion (see Table 3). The suitability is determined by multiple suitability factors, which are spatial attributes that serve as proxies for important drivers of location of LUC (see Verstegen, van der Hilst, et al., 2016 and Appendix S5). The land requirements are allocated sequentially: land is allocated to active land use n until the demand for land use n in that year is met, before proceeding to the allocation of land to active land use m (See Appendix S5).

2.2 | Global context and ethanol demand

The developments in the global supply and demand of commodities and related land use requirements depend on global socio-economic developments. This study makes use of the SSP2 scenario of the Shared Socio-economic reference Pathways (O'Neill et al., 2014, 2017). This SSP scenario was selected as it represents global development in line with historical patterns and is considered the middle of the road or the central pathway (O'Neill et al., 2017). In this study, the projections for developments in population and GDP at a national level are based on the data of IIASA (2012).

The global ethanol demand is exogenous to the modelling framework and is based on the outlook of IEA and OECD (2014), see Appendix S2. In order to isolate the effect of the increased ethanol demand on LUC dynamics from the combined effect of an increased demand of all biofuels, only the demand for ethanol is included.

The amount of land required to meet the global demand for commodities (including biofuels) depends on the productivity of the agricultural sector. In line with the storyline of SSP2, it is assumed that historical productivity trends in crops and livestock are continued towards 2030. The developments in agricultural productivity in each of the world regions in MAGNET are based on FAO (2003) and Stehfest et al. (2014). Additional explanation and full quantification of the outlook for the world and for Brazil specifically can be found in Appendix S3.

2.3 | LUC mitigation measures

The effects of measures to avoid undesired LUC resulting from an increased biofuel demand are evaluated using a scenario approach. The measures included in this study have been identified as potential promising strategies to avoid LUC (Al-Riffai et al., 2010a; Chum et al., 2011; de Wit, Londo, & Faaij, 2011; Melillo et al., 2009; Wicke et al., 2012). Three key measures to avoid LUC are assessed:

1. **Improved agricultural productivity:** Many studies indicated that the future extent of LUC depends on the development in crop and livestock productivity (Chum et al., 2011; Dornburg et al., 2010; Warner et al., 2014; Wicke et al., 2012; Witcover, Yeh, & Sperling, 2013). By improving agriculture productivity, increased production of biomass for food and non-food production can potentially take place without expanding the agricultural area. Considering the large area in use for crop production ($\sim 50 \times 10^6$ ha) and pastures ($\sim 150 \times 10^6$ ha) in Brazil (2012) (CONAB 2015, FAO 2015, IBGE 2006, 2013a,b), a slight increase in productivity could result in large areas of “available” land (Martha, Alves, & Contini, 2012). In this study, it is assessed to what extent an increase in agricultural productivity contributes to the avoidance or mitigation of LUC resulting from an increase in biofuel production.
2. **A shift towards second-generation ethanol:** Several studies indicated that improvements in the efficiency of the bioenergy supply chains and a shift towards second-generation biofuels could contribute to mitigate LUC (Al-Riffai, Dimaranan, & Laborde, 2010b; Wicke et al., 2012). In this study, it is assessed to what extent efficiency improvements in the bioenergy supply chain and a shift towards second-generation biofuel production contribute to the mitigation of LUC.
3. **Strict land conservation policies:** Many of the negative environmental impacts associated with bioenergy production are related to conversion of natural vegetation to agricultural land. By protecting natural areas for the conversion to managed lands, undesired LUC could be mitigated. In this study, it is assessed to what extent strict policies and policy enforcement of the conservation of natural forest could contribute to the mitigation of LUC.

The scenarios on LUC mitigation measures are compared to a reference scenario in order to be able to assess the effect of these measures.

2.3.1 | Reference scenario

In the reference scenario, it is assumed that no additional measures on agricultural productivity, technical

developments in the ethanol sector, or conservation policies are implemented and that these will continue to develop according to historical trends (in line with SSP2).

The developments in agricultural productivity in Brazil in the reference scenario are based on historical yield developments (FAO, 2013a; IBGE 2013a) and multiple outlooks on agricultural production (FAO 2003; FIESP and ICONE 2012; OECD and FAO 2014; Stehfest et al., 2014). In the modelling framework, the absolute crop and livestock productivity is differentiated for each macro-region of Brazil based on regional yield figures (IBGE 2013a,b). The relative annual yield increase is assumed to be uniform throughout Brazil, see Table 1.

Regarding the technical developments in the ethanol sector, the reference scenario projects incremental improvements in the first-generation ethanol production chain. These include a shift towards fully mechanized harvesting, an increase in the sugar cane yield and the total recoverable

sugar (TRS) content of sugar cane, improvement of the efficiency of the conversion to ethanol and of the combined heat and power (CHP generation), and an increase in the mill capacity and related cost reductions due to economies of scale (Jonker et al., 2015), see Table 2 and Appendix S3.2.

In the reference scenario, only military areas, areas of indigenous people, and fully protected federal and state conservation units (Federative Republic of Brazil 2000; Gurgel et al., 2009) are excluded for conversion to other land use types (see Table 3 and Appendix S3.3). Other land use policies restricting areas for specific land uses such as the Forest Act (Soares-Filho et al., 2014; Sparovek, Berndes, Barretto, & Klug, 2012), the Sugarcane Agro-ecological Zoning (ZEA Cana, Manzatto, Assad, Baca, Zaroni, & Pereira, 2009; Almeida, 2012), and the Soy Moratorium (Gibbs et al., 2015; Rudorff et al., 2011) do not completely exclude areas for land use conversion (see Appendix S3.3)

TABLE 1 Current average agricultural productivity and assumptions on the development in agricultural productivity in Brazil for the reference scenario and the “high productivity” (HP) scenario. For more details, see Appendix S3

	2012 ^a	Reference scenario ^b		HP scenario ^b	
	Productivity t ha ⁻¹ year ⁻¹	Productivity increase %/year	Productivity in 2030 t ha ⁻¹ year ⁻¹	Productivity increase %/year	Productivity in 2030 t ha ⁻¹ year ⁻¹
Crops^c					
Sugar cane ^d	74.3	0.8	85.8	1.6	98.9
Wheat	2.3	0.7	2.6	1.5	3.0
Cereal crops ^e	4.9	1.4	6.3	2.8	8.1
Paddy rice	4.8	1.3	6.0	2.6	7.5
Oil seed crops ^f	2.7	0.9	3.1	1.8	3.5
Fibre crops ^g	3.5	1.4	4.5	2.8	5.8
Fruit and vegetables ^h	21.2	0.7	24.0	1.4	27.2
Other crops ⁱ	2.2	0.8	2.6	1.5	2.9
Livestock^j					
	Heads/ha	%/year	Heads/ha	%/year	Heads/ha
Extensive (87%)	0.5	1.6%	0.7	3.2	0.9
Intensive (13%)	1.8	0.3%	1.8	0.6	1.9

^aThe yield is the weighted average of the crop composition of the crop category in 2012 (relative contribution to total production) on a national level. The yield levels of individual crops are based on PAM data of IBGE (2013b) which equals the time series in FAOSTAT (FAO, 2013a). Total production is based on yield and total area derived from IBGE (IBGE 2006, 2013a).

^bThe developments in yield are expressed as an average annual increase in the time frame 2012–2030.

^cCrop categories are based on the crop categories included in the GTAP database which is used in the MAGNET model.

^dIn the MAGNET model, the crop category “sugar crops” includes both sugar cane and sugar beet. However, in Brazil only sugar cane is cultivated.

^eCereal crops include oats, rye, barley, sorghum, triticale, and corn. Corn contributes for 96% to the total coarse grain production in Brazil.

^fOil seed crops in Brazil consist mainly of soy (98%) and furthermore of olive, palm, sunflower, and castor.

^gFibre crops in Brazil include mainly cotton (98%) and also sisal, jute, flax, malva, and rami.

^hFruit and vegetables also include beans, roots, and tubers. High yields are mainly explained by the high moisture content of horticulture crops.

ⁱ“Other crops” include a.o.: coffee, tea, cacao, spices, tobacco, rubber.

^jAlthough there are multiple livestock systems in Brazil, two key categories are included in this study. Extensive refers to ranging livestock (on rangeland), while intensive refers to livestock grazing on planted pastures. Livestock production in feedlots is uncommon in Brazil (SCOT Consultoria 2014). Productivity increases in each system are based on historical trends, expert judgement of ICONE, and (Harfuch, Nassar, Zambianco, & Gurgel, 2016; SCOT Consultoria 2014). In addition to an increase of the productivity in each system, there could be a shift from extensive to intensive livestock systems towards 2030. In 2012, the extensive livestock systems contributed 13% to the total production and the intensive systems contributed 87%. The rate of shifting from extensive systems to intensive systems is endogenous to the MAGNET model.

TABLE 2 Technological change in feedstock cultivation and conversion technology in ethanol sector for the reference scenario and second-generation scenario (see also Appendix S3)

		2030 scenarios			
		2012	Reference	2nd-gen sugar cane ^a	2nd-gen eucalyptus ^b
Cultivation	Sugar cane yield ^c	74.3 t ha ⁻¹ year ⁻¹	0.8%/year	1.6%/year	1.6%/year
	SC TRS ^d	136.4 kg/t	0.5%/year	0.5%/year	0.5%/year
	SC Harvest ^e				
	Manual	64%	5%	5%	5%
	Mechanical	36%	95%	95%	95%
	Eucalyptus Yield ^f	40.7 m ³ /ha	–	–	2.0%
Ethanol production	Feedstock ^a	Sugar cane	Sugar cane + SC straw	Sugar cane + SC straw	Sugar cane + SC straw + eucalyptus
	Technology	First gen	Improved first gen	Improved first- + second-gen SC	50% first- + second-gen SC, 50% second-gen EU
	Efficiency first-generation EtOH ^a	0.89%	0.1%/year	0.1%/year	0.1%/year
	Efficiency second-generation EtOH ^b	n.a	n.a	1.0%/year	1.0%/year
	Efficiency CHP ^b	76%	0.4%/year	0.7%/year	0.7%/year

^aThe overall ethanol production efficiency in 2012 is based on an extraction efficiency of 98%, extraction losses of 0.5%, a fermentation efficiency of 92%, and a distillation efficiency of 99%. The efficiency improvement is defined in % efficiency improvement per year. As the conversion from sugars to ethanol is a mature technology, only marginal efficiency improvements are expected, based on Jonker et al. (2015).

^bEfficiency improvements are defined in % efficiency improvement per year and are based on Jonker et al. (2015).

^cSugar cane yield in 2012 is derived from PAM data of IBGE (2013a). The yield increase in the reference scenario is based on historical trends (IBGE 2013a) and Jonker et al. (2015). In the second-generation scenarios it is assumed the yield increase is twice as high as in the reference scenario. This is still within the range provided by other outlooks of (FIESP and ICONE 2012; OECD and FAO 2014).

^dTotal recoverable sugar (TRS) levels are based on MAPA (2013). Although continuation of fluctuations are expected due to the sensitivity of TRS for weather conditions, a general upward trend of 0.5%/year is expected from 136 kg/t in 2012 to 149 kg/t in 2030 based on Leal, Walter, and Seabra (2013) and Jonker et al. (2015) and in line with the historical trends provided by MAPA (2013).

^eThe mechanization rate increased rapidly between 2004 and 2012 (CONAB 2008, 2013a, 2013b). In line with the green protocol (Etanol Verde 2007a, 2007b) and the law of São Paulo State (2002), it is assumed that manual harvest is (almost) phased out by 2014.

^fEucalyptus yield is based on the figures provided by ABRAF (2013). The yield developments are based on Jonker et al. (2015). 1 m³ of eucalyptus is assumed to correspond with 0.5 tonne dry matter.

and are therefore not excluded for agricultural expansion in this study. In Brazil, deforestation is (to a certain extent) legal according to the Forest Code.

2.3.2 | Improved agricultural productivity

In the high productivity (HP) scenario, it is assumed that the annual yield increase is twice as high compared to the reference scenario. The resulting growth rates and absolute yield figures for 2030 are cross-checked with historical yield developments, maximum attainable yields in Brazil, and agricultural productivity development elsewhere in the world to ensure optimistic yet realistic yield figures. Table 1 provides an overview of the projected yield increases for crops and livestock systems in Brazil according to the Reference and the HP scenario (see also Appendix S3).

2.3.3 | Shift towards second-generation ethanol

Regarding the LUC mitigation measure on the shift towards second-generation ethanol production, two options are assessed:

1. Improved first-generation sugar cane ethanol in combination with second-generation ethanol from bagasse and sugar cane straw.
2. A shift from first-generation sugar cane ethanol to second-generation ethanol from eucalyptus.

In the scenario of second-generation ethanol from sugar cane, the same developments in sugar cane cultivation as in the reference scenario are assumed. However, it is assumed that in the processing, the efficiency improvement

TABLE 3 Excluded areas in the reference scenario and the strict conservation policy (CP) scenario. As some of the excluded areas geographically overlap, the total excluded area is not equal to the sum of excluded areas

Excluded areas	Area (1,000 km ²)	Reference scenario	Strict CP scenario
Military areas ^a	48	✓	✓
Indigenous areas ^b	972	✓	✓
Federal conservation areas ^{b,c}	361	✓	✓
State conservation areas ^{b,c}	146	✓	✓
Forest land ^d	4,529	–	✓
Total excluded land (1,000 km ² , % of total area of Brazil)		1,452 (17%)	4,678 (55%)

^aBased on (Gurgel et al., 2009) and data of the Ministério do Meio Ambiente Brasil (MMA 2014).

^bBased on (Gurgel et al., 2009) and the spatial data from UFG (2015).

^cFederal and state conservation areas include both fully protected (Proteção Integral) areas and sustainable use (Uso Sustentável) areas (SNUC, Federative Republic of Brazil 2000). In this study, only the areas defined as “fully protected” areas are excluded as protection is enforced in those conservation units, whereas “sustainable use” still allows for land use changes.

^dThe area of forested land is based on the initial land use map of PLUC in 2012 (see Section 13), which is based on the data of IBGE (IBGE 2006, 2013a) and GlobCover (ESA 2010).

rate in ethanol conversion and of the CHP is higher and that in addition to bagasse, also sugar cane straw is used in the CHP. In addition, from 2020 onwards a shift to integrated first- and second-generation ethanol from sugar cane is assumed.

The scenario of second-generation ethanol production from eucalyptus is similar to the scenario on second generation of sugar cane, but from 2020 onwards a shift towards second-generation ethanol from eucalyptus is assumed. The techno-economic developments in the ethanol sector are based on the work of Jonker et al. (2015). In Table 2 (and Appendix S3) an overview of the scenarios on the developments in ethanol sector is provided.

2.3.4 | Strict land conservation policies

In the conservation policy (CP) scenario, it is assumed that, in addition to the areas protected in the reference scenario, no natural forest can be converted from 2015 onwards.

2.4 | Runs of the MAGNET-PLUC modelling framework

The MAGNET model and the PLUC model have a synchronized starting point for Brazil for their projections: the land use system of 2012. Both models are calibrated and

validated for the land use dynamics between 2006 and 2012, based on historical data. The elasticities in MAGNET and the suitability factors and order of allocation in PLUC are selected to best reproduce the LUC patterns observed in this time frame, see Verstegen, Karssenberg, van der Hilst, and Faaij (2016) and Verstegen, van der Hilst, et al. (2016). The land availability in each macro-region and the areas excluded for conversion to other land use types are harmonized between PLUC and MAGNET. The 5-year intervals of the land use type requirements from the MAGNET model are interpolated to generate a time series of annual demands for each active land use type in each macro-region, which serves as the input for the PLUC model. The different crop types included in MAGNET (cereals, wheat, paddy rice, oil crops, fruit and vegetables, fibre crops and other crops) are aggregated to the land use type “cropland” in PLUC. In addition, eucalyptus (for second-generation ethanol) and planted forest are combined in one land use class “planted forest.”

The MAGNET-PLUC modelling framework is run for the reference scenario, the scenarios on the LUC mitigation measures (high agricultural productivity, shift to second-generation ethanol from sugar cane, shift to second-generation ethanol from eucalyptus, and strict conservation policies), and a scenario in which the LUC mitigation measures are combined (high agricultural productivity, shift to second-generation ethanol from sugar cane, and strict conservation policies). All scenarios are run with and without the additional global demand for ethanol towards 2030, in order to be able to distinguish the effect of the increased ethanol demand on LUC dynamics from the expected LUC without the ethanol demand and to distinguish the effect of each measure on the LUC from the increased ethanol demand from the projected LUC without this measure (see Table 4). In the runs without an additional demand for ethanol, it is assumed that the global demand for ethanol remains at the level of 2013. It is imposed to the MAGNET model that in the scenario with the additional global ethanol demand, the developments in the production of crops and livestock in Brazil are the same as in the scenario without the additional ethanol demand. Therefore, no displacements effects occur outside Brazil and are not transferred to the rest of the world. Consequently, in this study no leakage effects are obscured and the effects of the LUC mitigation measures in Brazil can be properly evaluated.

2.5 | GHG emissions

The projections of the land use dynamics are the input for the GIS-based calculation of LUC-related GHG emissions resulting from the increase in global ethanol demand. LUC affects the SOC and the carbon sequestered in above and below ground biomass. The soil and biomass carbon stocks

TABLE 4 Overview of the scenario runs using the MAGNET-PLUC model framework to enable quantifying the impact of an additional global ethanol demand on land use dynamics and related carbon stock emissions in Brazil

	Scenarios to 2030											
	Reference scenario without additional ethanol demand	Reference scenario with additional ethanol demand	High agriculture productivity scenario without additional ethanol demand	High agriculture productivity scenario with additional ethanol demand	Shift towards second-generation sugar cane ethanol production, without additional ethanol demand	Shift towards second-generation sugar cane ethanol production, with additional ethanol demand	Shift towards second-gen eucalyptus ethanol production, without additional ethanol demand	Shift towards second-gen eucalyptus ethanol production, with additional ethanol demand	Scenario with strict conservation policies, without additional ethanol demand	Scenario with strict conservation policies, with additional ethanol demand	Scenario with all LUC mitigation measures, without additional ethanol demand ^a	Scenario with all LUC mitigation measures, with additional ethanol demand ^a
Abbreviation	Ref	Ref EtOH	HP	HP EtOH	2 nd SC	2 nd SC EtOH	2 nd EU	2 nd EU EtOH	CP	CP EtOH	All	All EtOH
Global development towards 2030	Synchronized for all scenarios based on SSP2											
Additional ethanol in 2030 compared to 2013	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes	–	Yes
LUC mitigation measures	–	–	Yes	Yes	–	–	–	–	–	–	Yes	Yes
Improved agricultural productivity	–	–	–	–	Yes	Yes	–	–	–	–	Yes	Yes
Second-generation EtOH sugar cane	–	–	–	–	–	–	–	–	–	–	Yes	Yes
Second-generation EtOH eucalyptus	–	–	–	–	–	–	Yes	Yes	–	–	–	–
Strict conservation policies	–	–	–	–	–	–	–	–	Yes	Yes	Yes	Yes

^aIn the scenario “all measures” it is assumed that all LUC mitigation measures are combined: high agricultural productivity, shift to second-generation ethanol from sugar cane, and a strict conservation policy in which all natural forest is protected.

depend on various factors of which most are spatially heterogeneous, such as land use, soil type, and climate conditions. The total changes in carbon stocks in the time frame 2012–2030 are calculated spatially explicitly for all scenarios following the IPCC guidelines (IPCC 2006) accounting for the difference between the carbon stocks before (2012) and after (2030) conversion. The LUC-related GHG emissions allocated to ethanol are calculated as the total LUC-related GHG emissions resulting from an additional ethanol demand divided by the total ethanol production that can be obtained in 20 years. The amortization period of 20 years is in line with the IPCC guidelines (2006). A more detailed description of the calculations and all input data can be found in Appendix S6.

3 | RESULTS

The results of MAGNET show an increase in global ethanol demand from 95.6×10^9 L ($2.2 \text{ EJ}_{\text{HHV}}$) in 2012 to 168×10^9 L ($3.9 \text{ EJ}_{\text{HHV}}$) in 2030. In this time frame, the ethanol production in Brazil is projected to more than double from 23.9 to 54.2×10^9 L (0.6 – $1.3 \text{ EJ}_{\text{HHV}}$), which corresponds to an increase in the global market share from 25% to 32%. The difference in ethanol production in Brazil in 2030 between the additional ethanol scenario and the no additional ethanol scenario (in which it remains at the level of 2013 = 27×10^9 L) is 26×10^9 L. In addition to the increase in ethanol, also the production of crops (82%), livestock (24%), and wood products (20%) are projected to increase significantly in Brazil towards 2030.

3.1 | Land use dynamics towards 2030 in the reference scenario (no measures)

In the absence of an additional ethanol demand, land requirements for agricultural crops (excluding sugar cane) in Brazil are expected to increase significantly (see Table 5), mainly due to an increase in the area for soy of ~160%. In addition, the land requirements for planted forest and planted pasture are projected to increase towards 2030. This is mainly at the expense of natural forest, grass and shrubland, and rangeland, see Figure 2 and Table 5 (reference scenario without additional ethanol demand). Expansion of cropland is projected to occur mainly in Mato Grosso and Goiás at the expense of previously abandoned agricultural land and rangeland. Planted pastures are expected to expand mainly in Mato Grosso, Mato Grosso do Sul and Goiás, at the expense of forest and grass and shrubland. Planted forest is projected to expand mainly in Bahia, Minas Gerais, and Rio Grande do Sul, primarily at the expense of grass and shrubland and natural forest. The projected loss of 24×10^6 ha natural vegetation is expected to occur mainly in Mato Grosso and Goiás, see Figure 3.

3.2 | LUC and related GHG emissions in the reference scenario (no measures) resulting from an additional ethanol demand

The doubling in ethanol production between 2012 and 2030 is projected to result in an increase in the land requirements for sugar cane production from 10.1×10^6 ha in 2012 to 13.6×10^6 ha in 2030 (3.5×10^6 ha corresponds to 0.4% of total land area of Brazil) see Table 5. Sugar cane is expected to expand foremost in Mato Grosso do Sul, Goiás, and São Paulo, predominantly at the expense of cropland (58%), and to a lesser extent at the expense of grass and shrubland (19%) and rangeland (14%) (see Figure 3). However, the expansion of sugar cane also affects the rest of the land use dynamics. When compared to the land use system in 2030 in the scenario without the additional ethanol demand, sugar cane expands in areas which would otherwise be in use by other land use types, mainly by cropland (see Table 5). This is partly buffered by an increased productivity of cropland, but it is also projected to result in the conversion of other land use types to cropland elsewhere: cropland is projected to expand in areas which would in the absence of an ethanol demand, be in use as rangeland grass and shrubs, natural forest, planted pasture, abandoned agricultural, and planted forest (0.1×10^6 ha) mainly in the state of Mato Grosso and Pará. The expansion of cropland in rangeland areas is partly absorbed by an increase in productivity of rangeland and a shift from rangeland to planted pasture, but is also projected to result in the expansion of 0.4×10^6 ha rangeland to, for example, planted forest, planted pasture, and grass and shrubs. However, there are also opposite effects: 1.6×10^6 ha is projected to remain natural vegetation, which would have been converted to sugar cane or other managed land in a scenario without additional ethanol demand.

The projected net effect of the additional demand for ethanol (measured as the land use in 2030 in the scenario with an additional ethanol demand compared to the land use in 2030 in the scenario without an additional ethanol demand) is a decrease in rangeland, planted forest, and cropland, but also a loss of grass and shrubland and forest, see Table 5. The loss of forest is projected to occur in Mato Grosso do Sul, Goiás, and Pará. The loss of grass and shrubland occurs mainly in São Paulo and Mato Grosso do Sul, see Figure 3.

The projected net loss of natural vegetation of 0.9×10^6 ha equals a loss of 0.26 ha of natural vegetation per ha of sugar cane or 75×10^{-9} ha/MJ (Figure 6a). The LUCs related to the additional ethanol demand in 2030 result in a total carbon loss of 86×10^9 kg C, which equals 26 g $\text{CO}_2\text{-eq/MJ}$, see Figures 4 and 6. The loss of carbon is partly caused by the loss of natural vegetation

TABLE 5 The land use changes between 2012 and 2030 for all scenarios with (EtOH) and without (No EtOH) the additional ethanol demand per land use type in Mha. “Delta” indicates the differences in land use in 2030 between the scenarios with and without the additional ethanol demand, that is, the land use change resulting from the additional ethanol demand in 2030

		Land use change in Mha compared to 2012							
Scenario 2030		Sugar cane	Cropland	Planted pasture	Rangeland	Planted forest	Grass and shrubs	Natural Forest	Abandoned
Reference scenario	No EtOH	0.1	32.1	7.8	−10.2	2.9	−12.0	−12.0	−8.8
	EtOH	3.7	31.9	7.2	−11.6	2.6	−12.8	−12.1	−8.8
	Delta	3.5	−0.2	−0.6	−1.4	−0.3	−0.8	−0.1	−0.1
High agricultural productivity	No EtOH	−1.0	26.3	3.4	−13.1	2.4	−6.6	−5.8	−5.5
	EtOH	2.1	26.1	3.0	−14.3	2.2	−7.2	−6.0	−5.9
	Delta	3.1	−0.2	−0.4	−1.2	−0.2	−0.6	−0.2	−0.4
2 nd -generation ethanol from sugar cane	No EtOH	−2.4	32.8	7.7	−9.5	2.9	−11.5	−11.5	−8.5
	EtOH	−0.6	32.6	7.4	−10.3	2.8	−11.6	−11.6	−8.6
	Delta	1.8	−0.2	−0.3	−0.9	−0.2	−0.1	−0.1	−0.1
2 nd -generation ethanol from eucalyptus	No EtOH	−3.5	33.0	7.4	−9.2	3.9	−11.6	−11.4	−8.5
	EtOH	−2.7	32.9	7.2	−9.8	4.3	−11.9	−11.7	−8.4
	Delta	0.8	−0.1	−0.2	−0.5	0.5	−0.3	−0.4	0.1
Strict conservation policies	No EtOH	−0.2	25.9	4.3	−17.7	−0.4	−6.6	0.0	−5.2
	EtOH	3.2	25.5	3.5	−19.1	−0.8	−7.3	0.0	−4.9
	Delta	3.4	−0.4	−0.9	−1.4	−0.3	−0.7	0.0	0.3
All measures	No EtOH	−2.6	23.6	1.7	−17.0	1.2	−4.2	0.0	−2.7
	EtOH	−0.9	23.5	1.4	−17.8	1.0	−4.2	0.0	−2.9
	Delta	1.8	−0.2	−0.3	−0.8	−0.2	0.0	0.0	−0.2

but also by the loss of rangeland and is mainly due to the loss of SOC (Figure 6). Losses are projected to occur predominantly in the state of Sao Paulo, Goiás, and Mato Grosso do Sul. In the same regions, additional carbon is sequestered where sugar cane expands at the expense of cropland, as sugar cane has more above and below ground biomass compared to cropland as well as higher SOC levels due to reduced tillage and higher input levels.

3.3 | LUC mitigation measures

3.3.1 | High agricultural productivity

In the high agricultural productivity (HP) scenario, the land requirements in 2030 for crops, livestock (rangeland and planted pastures), and planted forest are much lower compared to the reference scenario with no measures, see Table 5. However, managed land still expands significantly compared to 2012 (see Table 5 and the bar graphs in Figure 5). The expansion patterns are similar to the reference scenario (see maps Figure 5). When the additional demand of ethanol is accommodated, 3.1×10^6 ha additional sugar cane is required in 2030. This is 0.5×10^6 ha lower compared to the reference scenario with ethanol due to the

higher sugar cane yield, see Table 5. Sugar cane is projected to be cultivated in areas which would in the absence of the ethanol demand be predominantly in use for crops. In turn, crops are cultivated in areas which would otherwise be rangeland, grass and shrubs, and natural forest. In total, 0.8×10^6 ha of natural vegetation is additionally lost when the ethanol demand is accommodated, which equals a loss 0.25 ha natural vegetation per ha of sugar cane or 62×10^{-9} ha/MJ, see Figure 6a. The projected LUC dynamics caused by the additional ethanol demand result in 24 g CO₂-eq/MJ ethanol, which is 2 g CO₂-eq/MJ lower compared to taking no measures (Figure 6b).

3.3.2 | Shift to second-generation ethanol

Second-generation ethanol from sugar cane

If the additional demand for ethanol is accommodated by second-generation ethanol from sugar cane, a total 9.3×10^6 ha of sugar cane is estimated to be required in 2030. This is smaller compared to the area occupied by sugar cane in 2012 (-0.7×10^6 ha). However, it is larger compared to the scenario with the measure but without this additional ethanol demand in 2030, see Table 5. The additional areas of sugar cane are projected to be mainly

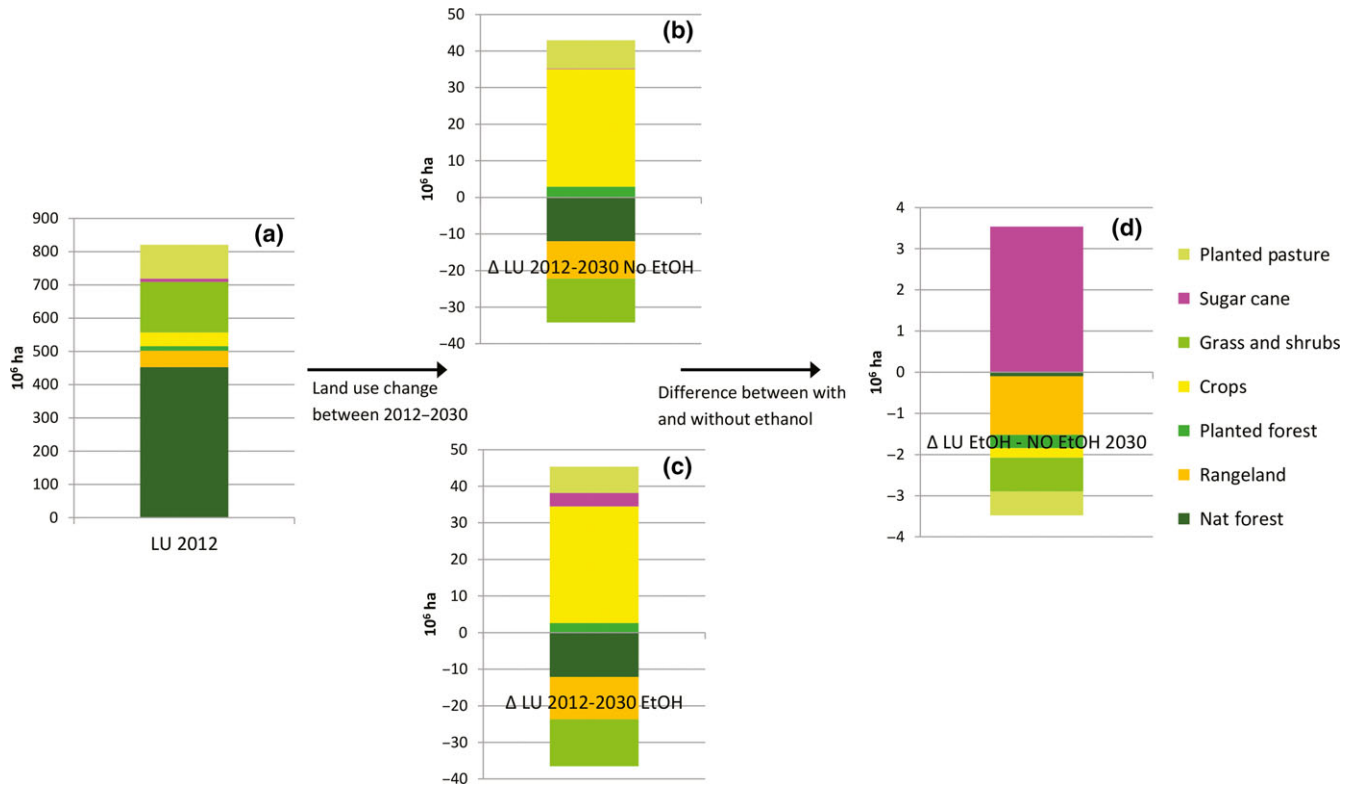


FIGURE 2 (a) Area of key land uses in Brazil in 2012 (in 10^6 ha), (b) area of land use change between 2012 and 2030 in the reference scenario without an additional ethanol demand (Δ LU 2012–2030 No EtOH, in 10^6 ha), (c) the reference scenario with an additional demand ($+26 \times 10^9$ L) of ethanol (Δ LU 2012–2030 EtOH, in 10^6 ha), and (d) the difference in land use in 2030 between with and without the additional ethanol demand (i.e., the LUC caused by the additional ethanol demand; in 10^6 ha), according to the MAGNET-PLUC projections

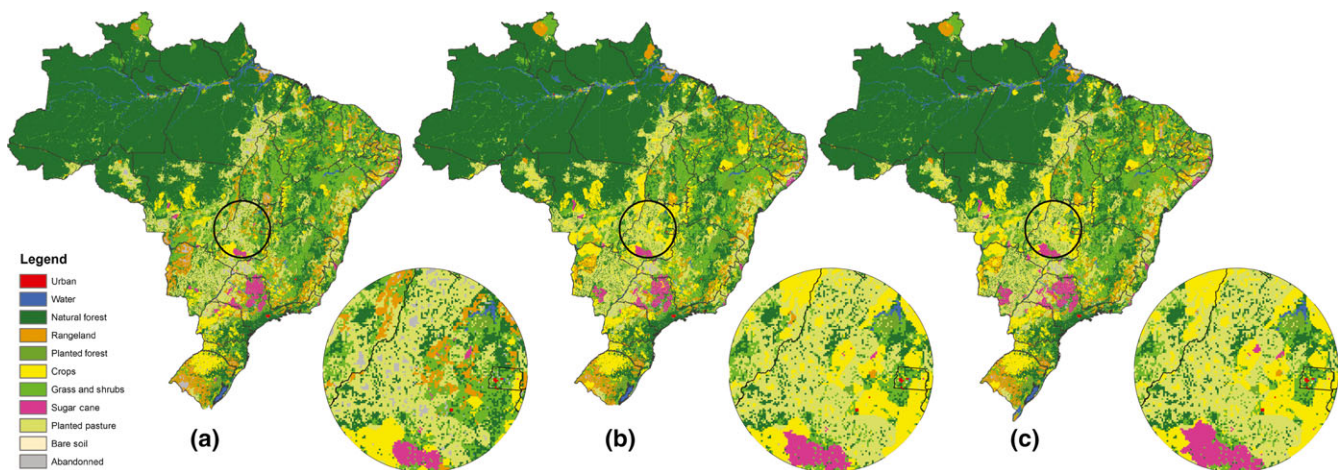


FIGURE 3 Land use patterns in Brazil in (a) 2012 and in 2030 for (b) the reference scenario without ethanol, and (c) the reference scenario with an additional ethanol demand of 26×10^9 L according to the MAGNET-PLUC projections. The enlargement shows the patterns in a part of the central south region (mostly the state of Goiás) in which many LUC dynamics occur

located in Sao Paulo, Mato Grosso, and Goiás, in areas which would in the absence of this ethanol demand be predominantly in use for cropland (71%). Consequently, cropland expands in Mato Grosso, Mato Grosso do Sul, and Minas Gerais mostly at the expense of rangeland, grass and shrubs, and forest. In total, 0.1×10^6 ha of forest and

0.1×10^6 ha of grass and shrubs are projected to be lost due to the expansion of sugar cane for ethanol. This equals a loss of 16×10^{-9} ha/MJ (Figure 6a). The LUC dynamics caused by the additional ethanol demand results in 14 g $\text{CO}_2\text{-eq/MJ}$, which is 46% lower compared to the scenario with no measures (Figure 6b).

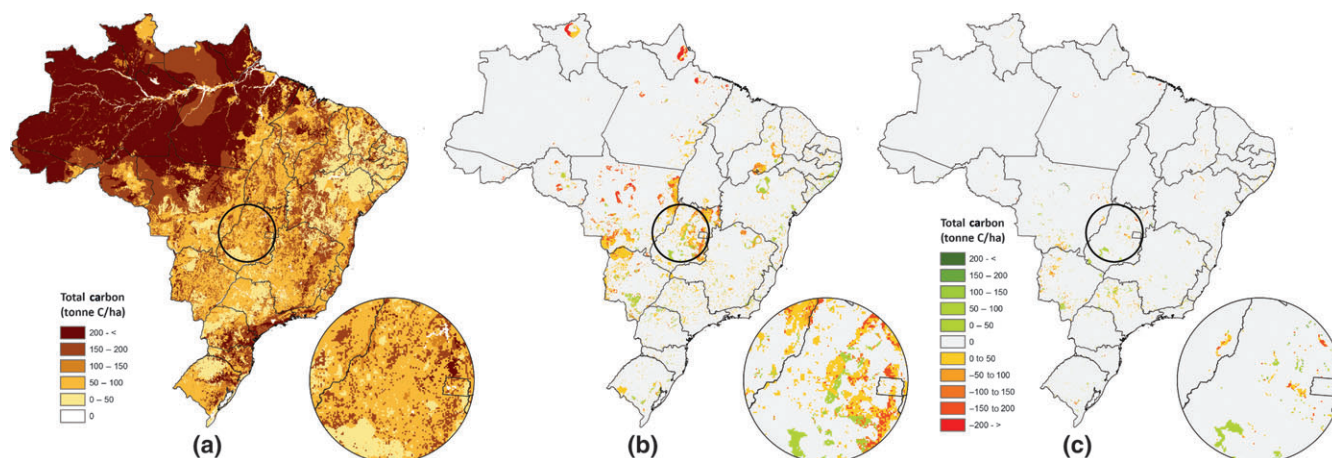


FIGURE 4 (a) Total carbon stock (above and below ground biomass and soil organic carbon) for the initial modelling year 2012, (b) the changes in carbon stock between 2012 and 2030 in the reference scenario without additional ethanol demand, and (c) the additional changes in carbon stock in 2030 in the reference scenario due to the additional ($+26 \times 10^9$ L) ethanol demand (compared to 2030 without ethanol)

Second-generation ethanol from eucalyptus

When the additional ethanol demand is partly accommodated by second-generation ethanol from eucalyptus, an extra 0.8×10^6 ha of sugar cane and 0.5×10^6 ha of eucalyptus are projected to be required in 2030 compared to scenario without the additional ethanol demand, see Table 5. Sugar cane expansion is projected to occur mainly in the areas which would otherwise be occupied by crops, which in turn move to areas which would have been occupied by rangeland, grass and shrubs, and natural forest in the absence of an additional ethanol demand. Eucalyptus (planted forest) is projected to expand predominantly at the expense of natural forest and grass and shrubs. In total, 0.4×10^6 ha of forest and 0.3×10^6 ha of grass and shrubs are lost due to the expansion of second-generation ethanol of sugar cane and eucalyptus. This equals a loss of 0.5 ha of natural vegetation per ha of sugar cane and eucalyptus or 55×10^{-9} ha/MJ (See Figure 6a). The LUC dynamics caused by the additional ethanol demand are projected to result in 10 g CO₂-eq/MJ (see Figure 6b). Thus, shifting to second-generation ethanol from eucalyptus results in relatively high losses of natural vegetation as eucalyptus expands mostly in shrubs and forested areas and no buffer effect (i.e., additional intensification) of other agricultural land occurs. However, high GHG savings are obtained due to the relatively high soil organic and biomass carbon stocks of eucalyptus plantations.

3.3.3 | Strict land conservation policies

Excluding all forest land from conversion to other land uses affects the dynamics of all land use types. The higher pressure on land causes more expansion at the intensive margin, resulting in lower land requirements for crops,

livestock, and forest plantations compared to the scenario in which no measures are applied. The 3.4×10^6 ha of extra sugar cane required to meet the additional ethanol demand is projected to expand mainly in Mato Grosso do Sul, São Paulo, and Goiás, in areas which would otherwise be in use for crops (59%) and grass and shrubs (22%). As in this scenario forest cannot be converted to other land uses, the loss of natural vegetation is all at the expense of grass and shrubs (0.7×10^6 ha), see Figures 5 and 6. This equals 0.21 ha natural vegetation per ha of sugar cane or 60×10^{-9} ha/MJ, see Figure 6a. The LUC dynamics caused by the additional ethanol demand are projected to result in 23 g CO₂-eq/MJ (see Figure 6b).

3.3.4 | All LUC mitigation measures

Combining an increase in agricultural productivity, a shift to second-generation sugar cane ethanol, and strict conservation policies is projected to result in considerably lower land requirements in 2030 compared to the scenario with no measures in 2030, see Table 5. To meet the additional ethanol demand, a supplementary 1.8×10^6 ha of sugar cane is required compared to the scenario with all measures taken but without the additional ethanol demand. However, the total sugar cane area of 9.1×10^6 ha in 2030 is still smaller compared to the level of 2012 (see Figure 5). Sugar cane expansion is projected to occur in Mato Grosso do Sul and Goiás mainly at the expense of cropland. The additional ethanol demand is projected to result in a net loss of 0.04×10^6 ha grass and shrubs, which equals 3×10^{-9} ha/MJ (see Figure 6a). The LUC dynamics caused by the additional ethanol demand results in 12 g CO₂-eq/MJ, which is 54% lower compared to taking no measures (see Figure 6).

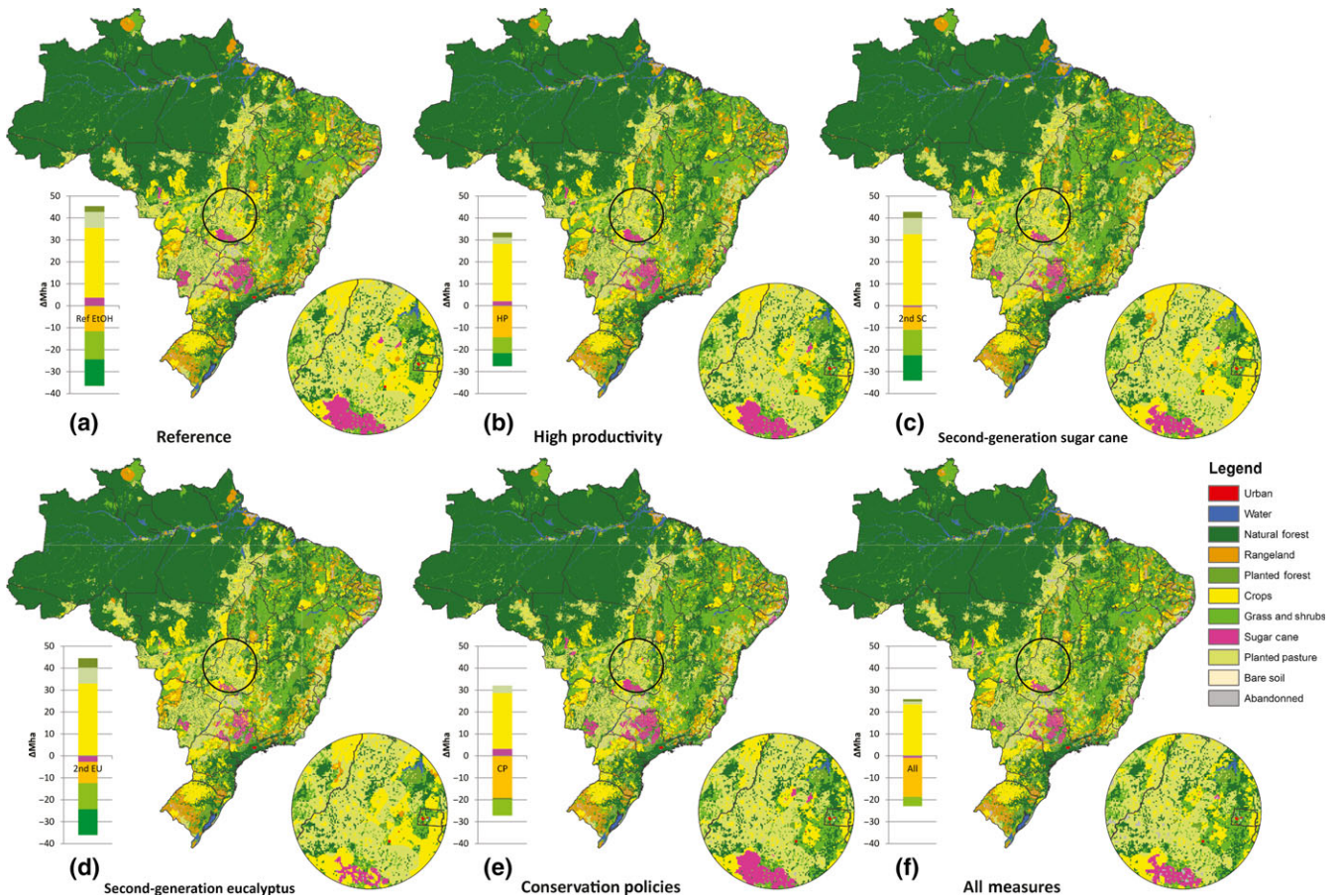


FIGURE 5 Land use patterns in 2030 for scenarios with the additional ethanol demand ($+26 \times 10^9$ L): (a) Reference, (b) high productivity, (c) shift to second-generation ethanol sugar cane, (d) shift to second-generation ethanol eucalyptus, (e) strict conservation policy, and (f) all measures combined. The bar graphs indicate the land use change compared to the reference year 2012. The enlargement shows part of the central south region (mostly the state of Goiás) in which many land use dynamics occur. The maps and the bar graphs share the same legend

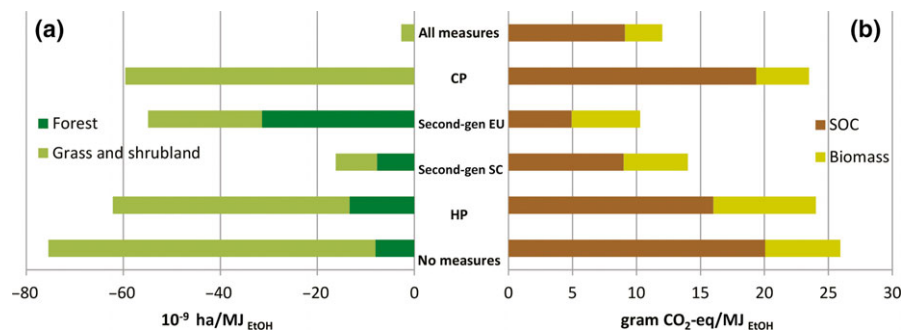


FIGURE 6 (a) Change in natural vegetation resulting from an increased ethanol production ($+26 \times 10^6$) in 2030 for all scenarios in ha/MJ ethanol. (b) GHG emissions due to biomass and soil organic carbon stock changes related to land use changes resulting from ethanol production in 2030 in g CO₂-eq/MJ ethanol. (No measures = reference scenario, HP = high agricultural productivity, 2nd-gen SC = shift to second-generation ethanol from sugar cane, 2nd-gen EU = shift to second-generation ethanol from eucalyptus, CP = strict conservation policies, all measures = combination of HP, 2nd-gen SC and CP)

4 | DISCUSSION

An increase in demand for ethanol is projected to result in both direct and indirect LUCs in Brazil. The projected 26×10^9 L increase in ethanol production in Brazil is

expected to require an additional 3.5×10^6 ha of sugar cane by 2030, when no regulation measures are taken. Although this area may seem relatively small compared to the entire land area of Brazil (0.4%), the absolute size of the additional land requirements is substantial, that is, the

area is almost the size of the Netherlands (4.1×10^6 ha). Sugar cane is expected to expand in the central south predominantly at the expense of agricultural land. This results in a higher productivity of agricultural land (expansion at the intensive margin) as well as expansion of agricultural land (expansion at the extensive margin). A clear cascading pattern can be observed in the modelling results: sugar cane expands predominantly at the expense of cropland, which in turns expands at the expense of mostly rangeland and planted forest, which successively results in the conversion of other land use types.

When no measures are taken, every ha of sugar cane expansion is projected to result in the loss of on average 0.26 ha of natural vegetation, which mainly occurs in the Cerrado and the Amazon. The loss of natural vegetation as well as the shifts between different agricultural land uses resulting from the additional ethanol demand is projected to result in the emission of ~ 26 g CO₂-eq/MJ. Given that life cycle emissions of ethanol production from sugar cane in Brazil are estimated at about ~ 20 g CO₂-eq/MJ (Macedo, Seabra, & Silva, 2008; Seabra, Macedo, Chum, Faroni, & Sarto, 2011; Walter et al., 2011), and assuming a default GHG emission of 94 CO₂-eq/MJ for gasoline (Edwards et al., 2017), GHG emission reductions of $\sim 51\%$ compared to gasoline can be obtained. This does not meet the threshold of 60% set by the European Commission in the RED for post-2015 installations (Directive (EU) 2015/1513, 2015) and it just meets the emission reduction requirements of $>50\%$ of the Renewable Fuel Standard (RTF2) for advanced fuels (EPA 2010). The United States Environmental Protection Agency (EPA) has approved sugar cane ethanol fuel pathway as an advanced fuel in the Renewable Fuel standard (EPA 2013). The LUC emissions calculated by EPA are, however, lower than found in this study which is partly caused by the assumed amortization period of 30 year, while in this study 20 years is assumed. It should be noted that after the amortization period, the carbon debt is repaid and large GHG reductions (79%) compared to gasoline can be obtained. The LUCs and related GHG emissions found in this study are specific for the indicated development in global ethanol demand towards 2030 ($+26 \times 10^9$ L). When also global biodiesel demand would be taken into account, projected LUC patterns will look differently, and related GHG emissions will likely be higher.

All LUC mitigation measures assessed in this study show potential to reduce the loss of natural vegetation (varying from 18% reduction for high agricultural productivity to 96% reduction when all LUC mitigation measures are applied). Also all LUC mitigation measures reduce the LUC-related GHG emissions resulting from ethanol production compared to the reference scenario, varying from 7% reduction for high agricultural productivity to 60% for shifting to second-generation from eucalyptus. Shifting to

second-generation ethanol production from eucalyptus is projected to result in a high loss of natural vegetation (55×10^{-9} ha/MJ), but also in the lowest LUC-related GHG emissions related to ethanol production (10 g CO₂-eq/MJ). Although these LUC-related GHG emissions are relatively low, there are other (environmental) concerns (e.g., loss of biodiversity, water stress) (Chum et al., 2011) why the conversion of natural vegetation to biofuel crops (in this case eucalyptus) is undesirable. Combining the LUC mitigation measures could prevent almost all loss of natural vegetation. However, it is projected to result in GHG emissions due to shifts between agricultural land uses resulting from an increased ethanol demand. Although shifting to second-generation ethanol (from either sugar cane or eucalyptus) is found to be the most suitable measure to reduce the LUC-related GHG emissions of biofuels, it is not an adequate way to cut GHG emissions of land use, LUC and forestry (LULUCF) in general as this measure does not affect the GHG emissions related to other LUC dynamics, which are much more prominent. Considering the whole land use system, increasing the agricultural productivity is the most effective way of reducing LUC-related emissions. Especially for the livestock sector, the potential for intensification and thereby reducing land use and GHG emissions is large (Martha et al., 2012). It should be noted that there are already ongoing efforts to increase agricultural productivity, invest in second-generation ethanol processing technologies, and reduce deforestation in Brazil.

Lapola et al. (2010) also projected that sugar cane expansion for ethanol production will predominantly take place in the central south. However, their projections show more expansion in São Paulo, Minas Gerais, Rio de Janeiro, and Paraná and more at the expense of rangeland. In contrast to this study, Lapola et al. (2010) also included an expansion of soy for biodiesel, which also affects land use dynamics especially in the northern part of the centre south. In addition, these differences in results can be explained by the fact that Lapola et al. (2010) projected land use for 2020, used an older initial land use map (from 1992), and included fewer active land use types and different suitability factors for the spatial allocation of land use (based on the occurrence of land use types in 2003 instead of historical land use transitions over time). In this study, the suitability factors and their respective weight have been calibrated for the transition period 2006–2012 (Verstegen, van der Hilst, et al., 2016).

Studies based on historical LUCs in Brazil indicate that in the past expansion of sugar cane mainly occurred at the expense of pasture land (Adami et al., 2012; Nassar & Moreira, 2013; Rudorff et al., 2010), while this study projects the majority of sugar cane expansion to take place at the expense of cropland. There are several reasons for this inconsistency. First of all, it depends on the reference year

that is selected for both for the historical LUC as well as for the projections. Historically, large areas of pasture land were first converted to cropland and subsequently converted to sugar cane. Depending on the reference year, this LUC is labelled as a transition from pasture to sugar cane, or from cropland to sugar cane. In this study, it is indicated that sugar cane is expected to expand mainly in areas which will be in use for cropland in 2030 in the scenario without the additional demand for ethanol. However, some of these areas are not in use for cropland yet. Secondly, as the (spatial) data on pastures and rangeland in Brazil is scarce, of poor quality and often contradictory, there are different interpretations of the amount, location and dynamics of pasture, rangeland, and grass and shrubs (Novaes et al., 2017). Thirdly, in this study, the land use dynamics were calibrated for the time frame 2006–2012. This includes the calibration of the order of land use allocation. The median of the probability distribution of the allocation order of the stochastic model setting (Verstegen, van der Hilst, et al., 2016) was used, in which planted pasture was allocated first. Therefore, sugar cane cannot expand over planted pasture within the same time step. This calibration was done for all land uses simultaneously and represents the best fit for total land use dynamics, but could be sub-optimal for just sugar cane. When better historical spatial data on land use and especially pasture and rangeland are available, calibration of LUC dynamics can be significantly improved.

The LUC-related GHG emissions of sugar cane ethanol in Brazil of 26 g CO₂-eq/MJ found in this study for the scenario without any measures are higher compared to the LUC-related GHG emission of sugar cane ethanol in general (9–20 g CO₂-eq/MJ) found in the studies of (Air Resource Board 2014; Al-Riffai et al., 2010b; Laborde, 2011; Overmars, Edwards, Padella, Prins, & Marelli, 2015). This can partly be explained by the fact that this study focusses on 2030 and include global mandates, whereas the studies of, for example, Al-Riffai et al. (2010b) and Laborde (2011) focus on the impact of EU biofuel policies in 2020. It can be expected that a higher demand for biofuels (and other agricultural commodities) results in more pressure on land and potentially higher LUC emissions, and that this is a non-linear relationship. That is, the LUC-related emission found in this study as well as in other studies directly relates to the magnitude of biofuels demand assumed as well as the demand for other land use functions. Also, in this study all displacement effects are modelled to occur within Brazil, so no leakage effects are projected to occur in the rest of the world. Therefore, the LUC-related emissions could be higher compared to studies assessing global LUC, as in Brazil a higher demand for agricultural land tends to result more easily in agricultural extension instead of yield increases compared to some other regions in the world (Laborde,

2011). Other explanations for differences between the studies are the differences in modelling approaches, system boundaries, assumptions made, and data input. The LUC-related emissions in tonne CO₂-eq per hectare per year found in this study are within the wide range of historical LUC-related emissions of sugar cane in Brazil identified by Novaes et al. (2017).

However, this is the first study combining global CGE model and a detailed land use model to quantify the LUC-related GHG emissions taking into account both macro-economic drivers as well as spatially explicit socio-economic and biophysical drivers of LUC and the spatial heterogeneity in carbon stocks. In addition, the focus of this study is on quantifying the impacts of different LUC mitigations measures. Including the LUC mitigation measures in the combined CGE–LUC modelling framework enables the assessment of the expansion at both the intensive margin and at the extensive margin. This is a step forward compared to other studies where the impact of (I) LUC mitigation measures is assessed ex-post to CGE modelling and at an aggregated geographical level (country or region; Gerssen-Gondelach, Wicke, Borzęcka-Walker, Pudelko, & Faaij, 2016; Brinkman, Wicke, & Faaij, 2017).

The MAGNET-PLUC modelling framework applied in this study has several limitations. The MAGNET model (like other CGE models) has several shortcomings: for example, the economy is represented through aggregated sectors with data that are a compromise between national precision and international consistency. Particularly, the dynamics of land markets is quite sensitive for assumed elasticities which are highly uncertain (Tabeau, Helming, & Philippidis, 2017). Furthermore, it is not able to adequately deal with uncertainties in policies (e.g., subsidies for ethanol or fossil fuels) and volatility of the currency market (e.g., high fluctuation in value of Brazilian Real, R\$). It is, however, a good model to assess the development in production of commodities in a single region (Brazil) in the context of global developments, as it combines the advantages of a global economic model including the explicit and consistent analysis of interactions between sectors and world regions, with the advantages of a region specific land transition approach. In addition, by updating the data for the sugar cane ethanol sector and by calibrating the model for LUC in Brazil (2006–2012) some of these key shortcomings have been addressed. The calibration and validation of the MAGNET-PLUC model for the 2006–2012 time frame ensure that it is able to replicate historical LUC patterns well. Model validation showed that the transition rules are well identified for sugar cane, crops, and planted pasture, but weakly defined for rangeland and planted forest. Since our current study is focused on sugar cane expansion, the weaker performance of the rangeland and planted forest classes are not expected to influence the

results of our current study much (Verstegen, van der Hilst, et al., 2016). The parametrization of this combined model is of course a strong simplification of highly complex interactions between socio-economic and environmental drivers of LUC at different geographical scales in the real system. Furthermore, by applying this parametrization to future projections, the potential changes in the relationship between LUCs and their explanatory processes in LUC are ignored (Verstegen, Karssenberg, et al., 2016). The modelling framework could be further improved by an increased integration of the models where, for example, the spatial allocation of land use of the PLUC model is fed back into MAGNET enabling to account for more detailed spatial variation in productivity and costs. Also, as demonstrated by Verstegen, van der Hilst, et al. (2016), there are many uncertainties related to the projections of the magnitude (in MAGNET) and the location (in PLUC) of LUC. Running all scenarios stochastically could provide information on the effect of uncertainties in the input data and model structure on the results and could show if the differences between the LUC mitigation measures are significant. However, both the MAGNET model and the Carbon module are not designed for Monte Carlo simulations. Although an uncertainty analysis provides more insight on factors affecting the accuracy of the results, it does not tackle all uncertainties related to LUC projections. As the deterministic runs of the scenarios in this study are all based on the same assumptions and the focus lies on relative differences instead of absolute results, it is deemed the results provide a good indication of the relative differences between the scenarios.

The GIS-based carbon module is based on the IPCC default values taking the spatial variability of carbon stocks due to land use, soil characteristics, and climate into account as well as the agricultural management and input level. However, these default values come with large uncertainty ranges (up to $\pm 90\%$; IPCC, 2006) and they do not account for specific local and temporal conditions (e.g., historical developments in land use and management). Including the carbon module in the assessment of error propagation in the different modelling components for all scenarios as done by Verstegen, Karssenberg, et al. (2016) and Verstegen, van der Hilst, et al. (2016) for the MAGNET-PLUC modelling framework could contribute to the quantification of the uncertainty in the effectiveness of the LUC measures. In addition, more and better data, especially on SOC levels, will improve the estimations of LUC-related GHG emissions. Furthermore, in this study an amortization period of 20 years is assumed thereby ignoring the timing of emissions related to LUC. However, the timing of GHG emissions can have significant impact on climate change (Kendall, Chang, & Sharpe, 2009) and can vary considerably depending on the fate of cleared

biomass assumed (Earles, Yeh, & Skog, 2012). Including the timing of emissions could potentially improve the estimation of the contribution to global warming.

Although there are several uncertainties regarding the exact location of LUC and amount of GHG emissions related to an increase in demand of bioethanol, this study shows that the implementation of LUC mitigation measures could have a substantial contribution to the reduction of LUC-related GHG emissions of ethanol. It should, however, be noted that the LUC emissions resulting from sugar cane expansion are relatively small compared to other major LUC trends in Brazil (e.g., deforestation related to (illegal) logging and land speculation, degradation of pastures, cropland expansion, agricultural management changes). In addition, all these dynamics interact. Therefore, focusing primarily on an (I)LUC factor of biofuel does not contribute to reducing overall GHG emissions. Instead, an integrated approach targeting all land uses is required to move towards sustainable land use. In addition to carbon, other environmental (e.g., impact on water and biodiversity) but also socio-economic impacts (e.g., impacts on rural economy and food security) of LUC dynamics should be taken into account in order to find sustainable land use solutions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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